Chapter 2

COST ESTIMATING METHODOLOGY

William M. Vatavuk
Innovative Strategies and Economics Group, OAQPS
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

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Contents

This chapter presents a methodology that will enable the user, having knowledge of the source being controlled, to produce study-level cost estimates for a control system to control that source. The methodology, which applies to each of the control systems included in this *Manual*, is general enough to be used with other "add-on" systems as well. Further, the methodology may also be applicable to estimating costs of fugitive emission controls and of other non-stack abatement methods.

Before presenting this methodology in detail, we should first discuss the various kinds of cost estimates and then define the cost categories and engineering economy concepts employed in making the estimates.

2.1 Types of Cost Estimates

As noted above, the costs and estimating methodology in this *Manual* are directed toward the "study" estimate, of ± 30% accuracy. According to Perry's *Chemical Engineer's Handbook*, a study estimate is "… used to estimate the economic feasibility of a project before expending significant funds for piloting, marketing, land surveys, and acquisition … [However] it can be prepared at relatively low cost with minimum data."[1] Specifically, to make a study estimate, the following must be known:

- Location of the source within the plant;
- Rough sketch of the process flow sheet (*i.e.*, the relative locations of the equipment in the system);
- Preliminary sizes of, and material specifications for, the system equipment items;
- Approximate sizes and types of construction of any buildings required to house the control system;
- Rough estimates of utility requirements (*e.g.*, electricity);
- Preliminary flow sheet and specifications for ducting and piping;
- Approximate sizes of motors required.[1]

In addition, an estimate of the labor hours required for engineering and drafting is needed, as the accuracy of an estimate (study or otherwise) is highly dependent on the amount of engineering work expended on the project.

There are, however, four other types of estimates, three of which are more accurate than the study estimate. These are:[1]

- *Order-of-magnitude.* This estimate provides "a rule-of-thumb procedure applied only to repetitive types of plant installations for which there exists good cost history". Its error bounds are greater than ± 30%. (However, according to Perry's, "… no limits of accuracy can safely be applied to it.") The sole input required for making this level of estimate is the control system's capacity (often measured by the maximum volumetric flow rate of the gas passing through the system). So-called "six-tenths factor" estimates (not to be confused with *factored* estimates) are examples of this type.

- *Scope* or *Budget authorization* or *Preliminary*. This estimate, nominally of ± 20% accuracy, requires more detailed knowledge than the study estimate regarding the site, flow sheet, equipment, buildings, etc. In addition, rough specifications for the insulation and instrumentation are also needed.

- *Project control* or *Definitive*. These estimates, accurate to within ± 10%, require yet more information than the scope estimates, especially concerning the site, equipment, and electrical requirements.

- *Firm* or *Contractor's* or *Detailed*. This is the most accurate (± 5%) of the estimate types, requiring complete drawings, specifications, and site surveys. Further, "[t]ime seldom permits the preparation of such estimates prior to an approval to proceed with the project."[1]

For the purposes of regulatory development, study estimates have been found to be acceptable, as they represent a compromise between the less accurate order-of-magnitude and the more accurate estimate types. The former are too imprecise to be of much value, while the latter are not only very expensive to make, but require detailed site and process-specific knowledge that most *Manual* users will not have available to them.

2.2 Cost Categories Defined

The names given certain categories of costs and what they contain vary considerably throughout the literature. Certain words like "capital cost" can have vastly different meanings, which can often lead to confusion, even among cost estimators. To avoid this confusion and, at the same time, provide uniformity in the *Manual* basic terms are defined in this chapter and will be used throughout. The terminology used is adapted from that of the American Association of Cost Engineers.[2] Although it has been developed for general use, it is readily adaptable to air pollution control system costing.

First, two general kinds of costs are estimated, *total capital investment* (TCI) and *total annual cost* (TAC). These are discussed below.

2.2.1 Elements of Total Capital Investment

The total capital investment includes all costs required to purchase equipment needed for the control system (termed *purchased equipment* costs), the costs of labor and materials for installing that equipment (termed *direct installation* costs), costs for site preparation and buildings, and certain other costs which are termed *indirect installation costs.* The TCI also includes costs for land, working capital, and off-site facilities.

Direct installation costs include costs for foundations and supports, erecting and handling the equipment, electrical work, piping, insulation, and painting. Indirect installation costs include such costs as engineering costs; construction and field expenses (*i.e.*, costs for construction supervisory personnel, office personnel, rental of temporary offices, etc.); contractor fees (for construction and engineering firms involved in the project); start-up and performance test costs (to get the control system running and to verify that it meets performance guarantees); and contingencies. Contingencies is a catch-all category that covers unforeseen costs that may arise, including (but certainly not limited to)"… possible redesign and modification of equipment, escalation increases in cost of equipment, increases in field labor costs, and delays encountered in start-up."[2]

These elements of total capital investment are displayed in Figure 2.1. Note that the sum of the purchased equipment cost, direct and indirect installation costs, site preparation, and buildings costs comprises the battery limits estimate. By definition, this is the total estimate "… for a specific job without regard to required supporting facilities which are assumed to already exist…"[2] at the plant. This would mainly apply to control systems installed in existing plants, though it could also apply to those systems installed in new plants when no special facilities for supporting the control system (*i.e.*, off-site facilities) would be required.

Where required, these off-site facilities would encompass units to produce steam, electricity, and treated water; laboratory buildings, railroad spurs, roads, and the like. It is unusual, however, for a pollution control system to have one of these units (*e.g.*, a power plant) dedicated to it. The system needs are rarely that great. However, it may be necessary—especially in the case of control systems installed in new or "grass roots" plants—for extra capacity to be built into the site generating plant to service the system. (A venturi scrubber, which often requires large amounts of electricity, is a good example of this.) It is customary for the utility costs to be charged to the project as operating costs at a rate which covers both the investment and operating and maintenance costs for the utility.

As Figure 2.1 shows, there are two other costs which may be included in the total capital investment for a control system. These are *working capital* and *land*. The first of these, working capital, is a fund set aside to cover the initial costs of fuel, chemicals, and other materials, as well as labor and maintenance. It usually does not apply to control systems, for the quantities of utilities, materials, labor, etc., they require are usually small. (An exception might be an oil-fired thermal incinerator, where a small supply (*e.g.*, 30-day) of distillate fuel would have to be available during its initial period of operation.)

Land may also be required. But, since most add-on control systems take up very little space (a quarter-acre or less) this cost would be relatively small. (Certain control systems, such as those used for flue gas desulfurization, require larger quantities of land for the process equipment, chemicals storage, and waste disposal.)

Note also in Figure 2.1 that the working capital and land are nondepreciable expenses. In other words, these costs are "recovered" when the control system reaches the end of its useful life (generally in 10 to 20 years). Conversely, the other capital costs are depreciable, in that they cannot be recovered and are included in the calculation of income tax credits (if any) and depreciation allowances, whenever income taxes are considered in a cost analysis. (In the *Manual* methodology, however, income taxes are *not* considered. See Section 2.3.)

Notice that when 100% of the system costs are depreciated, no salvage value is taken for the system equipment at the conclusion of its useful life. This is a reasonable assumption for add-on control systems, as most of the equipment, which is designed for a specific source, cannot be used elsewhere without modifications. Even if it were reusable, the cost of disassembling the system into its components (*i.e.*, "decommissioning cost") could be as high (or higher) than the salvage value.

2.2.2 Elements of Total Annual Cost

The Total Annual Cost (TAC) for control systems is comprised of three elements: *direct costs* (DC), *indirect costs* (IC), and *recovery credits* (RC),
which are related by the following equation:

$$TAC = DC + IC - RC \tag{2.1}$$

Clearly, the basis of these costs is one year, as this period allows for seasonal variations in production (and emissions generation) and is directly usable in profitability analyses. (See Section 2.3.)

Direct costs are those which tend to be proportional or partially proportional to the quantity of exhaust gas processed by the control system per unit time. These include costs for raw materials, utilities (steam, electricity, process and cooling water, etc.), waste treatment and disposal, maintenance materials, replacement parts, and operating, supervisory, and maintenance labor. Of these direct costs, costs for raw materials, utilities, and waste treatment and disposal are *variable*, in that they tend to be a direct function of the exhaust flow rate. That is, when the flow rate is at its maximum rate, these costs are highest. Conversely, when the flow rate is zero, so are the costs.

Semivariable direct costs are only partly dependent upon the exhaust flow rate. These include all kinds of labor, overhead, maintenance materials, and replacement parts. Although these costs are a function of the gas flow rate, they are not linear functions. Even while the control system is not operating, some of the semivariable costs continue to be incurred.

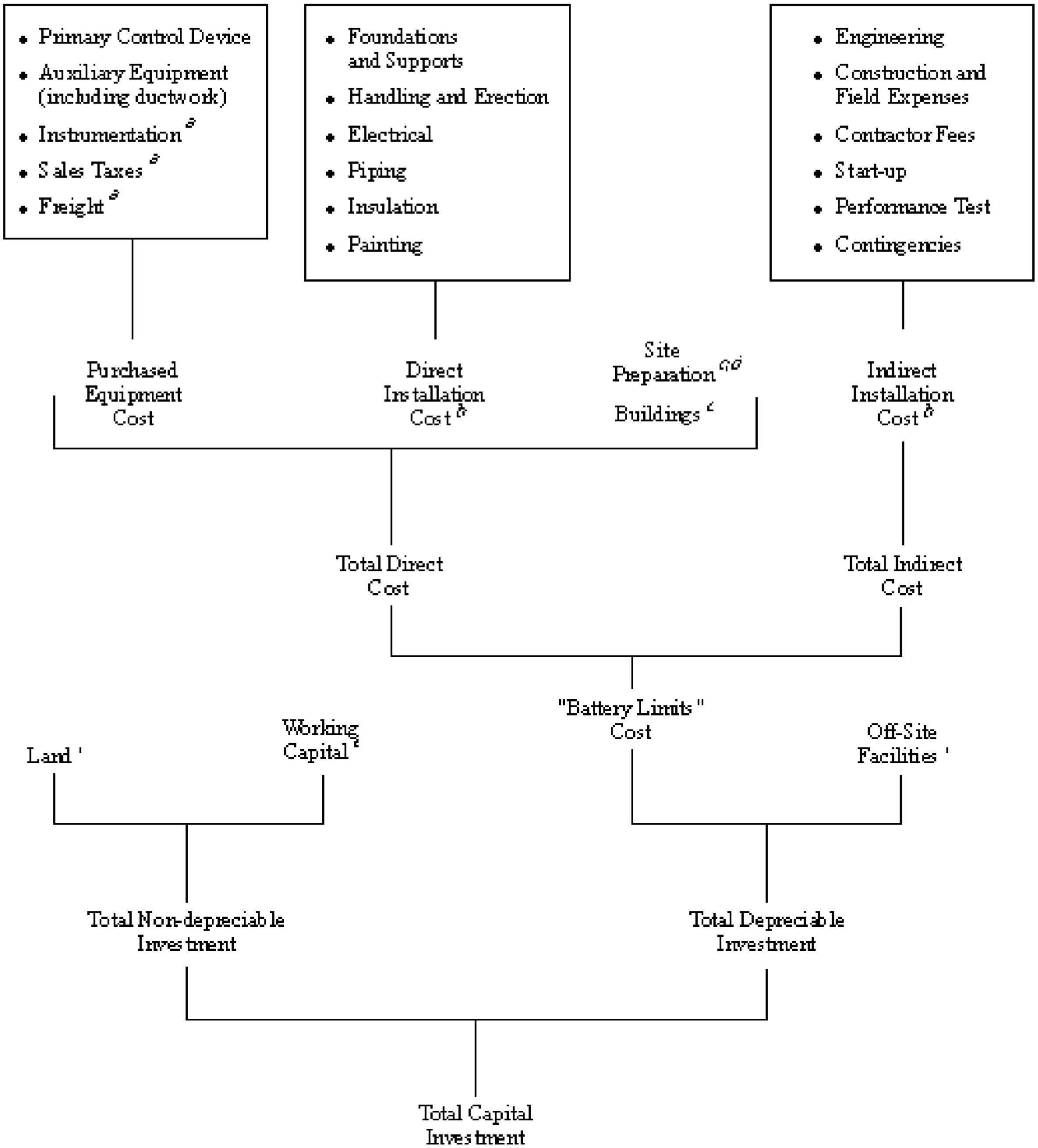
Indirect, or "fixed", annual costs are those whose values are totally independent of the exhaust flow rate and, in fact, would be incurred even if the control system were shut down. They include such categories as administrative charges, property taxes, insurance, and capital recovery.

Finally, the direct and indirect annual costs are offset by recovery credits, taken for materials or energy recovered by the control system, which may be sold, recycled to the process, or reused

Figure 2.2: Elements of Total Annual Cost

Figure 2.2: Elements of Total Annual Cost

| • Raw material |



[a] Typically factored from the sum of the primary control device and auxiliary equipment costs.
[b] Typically factored from the purchased equipment cost.
[c] Usually required only at "grass roots" installations.
[d] Unlike the other direct and indirect costs, costs for these items usually are not factored from the purchased equipment cost. Rather, they are sized and costed separately.
[e] Normally not required with add-on control systems.

Figure 2.1: Elements of Total Capital Investment

• Utilities
  - Electricity
  - Fuel
  - Steam
  - Water
  - Compressed air
• Waste treatment/ disposal

Variable

• Labor
  - Operating
  - Supervisory
  - Maintenance
• Maintenance materials
• Replacement parts

Semivariable

Direct Costs

• Overhead
  • Property taxes
  • Insurance
  • Administrative charges
  • Capital recovery

Indirect Costs

• Materials

Recovery

Total Annual Cost

| | | Credits
| • Energy |

elsewhere at the site. These credits, in turn, must be offset by the costs necessary for their processing, storage, transportation, and any other steps required to make the recovered materials or energy reusable or resalable. Great care and judgement must be exercised in assigning values to recovery credits, since materials recovered may be of small quantity or of doubtful purity, resulting in their having less value than virgin material. Like direct annual costs, recovery credits are *variable*, in that their magnitude is directly proportional to the exhaust flow rate. The various annual costs and their interrelationships are displayed in Figure 2.2. A more thorough description of these costs and how they may be estimated is given in Section 2.4.

2.3 Engineering Economy Concepts

As mentioned previously, the estimating methodology presented in Section 2.4 rests upon the notion of the "factored" or "study" estimate. However, there are other concepts central to the cost analyses which must be understood. These are (1) the time value of money, (2) cash flow, and (3) annualization.

2.3.1 Time Value of Money

The *time value of money* is based on the truism that "…a dollar now is worth more than the prospect of a dollar… at some later date."[3] A measure of this value is the interest rate which "… may be thought of as the return obtainable by the productive investment of capital."[3]

2.3.2 Cash Flow

During the lifetime of a project, various kinds of cash expenditures are made and various incomes are received. The amounts and timing of these expenditures and incomes constitute the *cash flows* for the project. In control system costing it is normal to consider expenditures (negative cash flows) and unusual to consider income (positive cash flows), except for product or energy recovery income. By the simplifying convention recommended by Grant, Ireson, and Leavenworth[3], each annual expenditure (or payment) is considered to be incurred at the end of the year, even though the payment will probably be made sometime during the year in question. (The error introduced by this assumption is minimal, however.) Figure 2.3, which shows three hypothetical cash flow diagrams, illustrates these end-of-year payments. In these diagrams, P represents the capital investment, while the A's denote the end-of-year annual payments. Note that in all diagrams, the cash flows are in *constant* (real) dollars, meaning that they do not reflect the effects of inflation. Also note that in the top

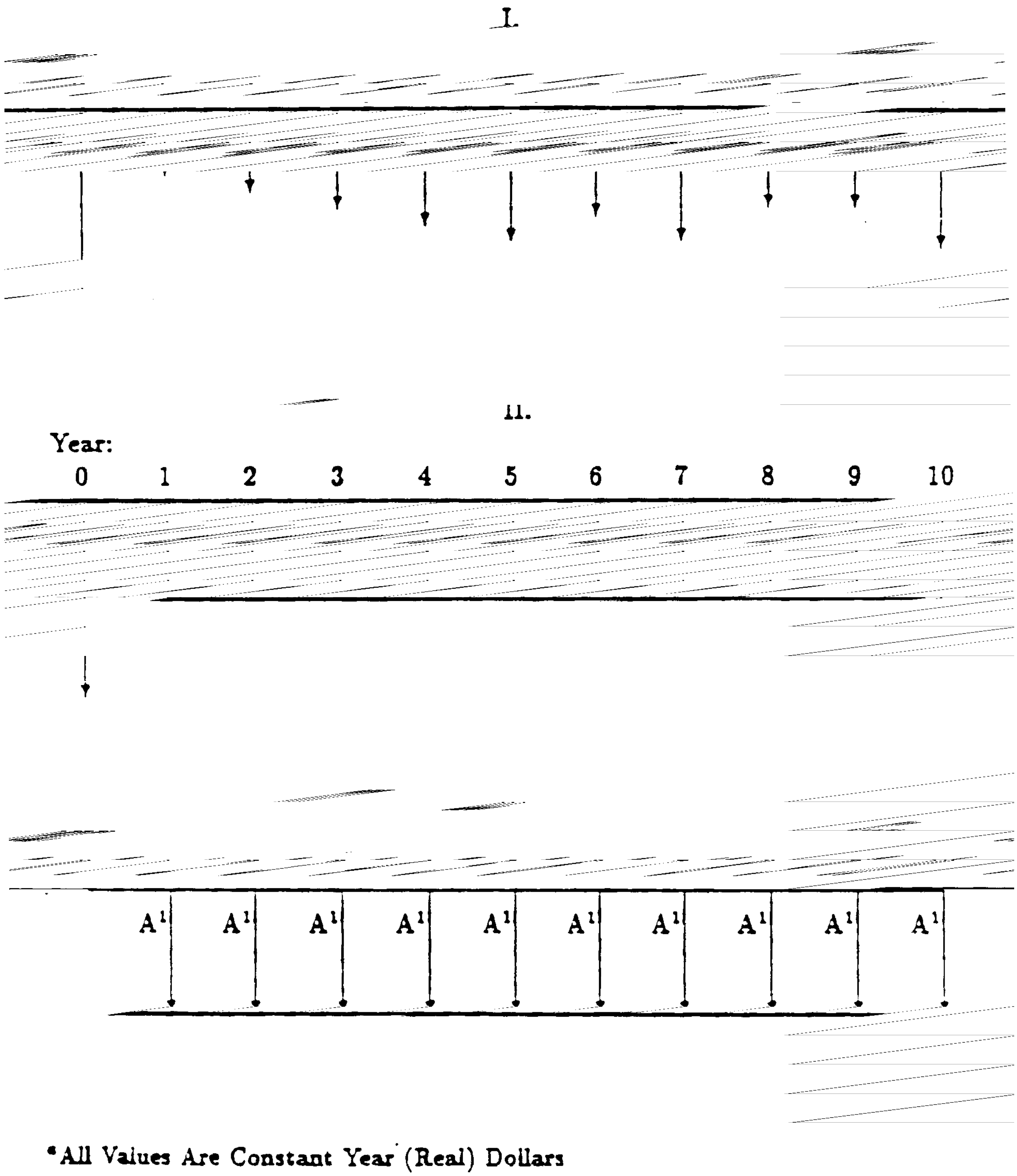


Figure 2.3: Hypothetical Cash Flow Diagrams

diagram (I), the annual payments are different for each year. (These represent the control system annual costs (exclusive of capital recovery) described in Section 2.2.) In reality, these payments would be different, as labor and maintenance requirements, labor and utility costs, etc., would vary from year to year. A generally upward trend in annual costs would be seen, however.

In diagram II, these fluctuating annual payments have been converted to equal payments. This can be done by calculating the sum of the *present values* of each of the annual payments shown in diagram I and *annualizing* the total net present value to equivalent equal annual payments via a capital recovery factor. (See discussion in the following paragraphs and in Section 2.3.3.) Alternatively, it is adequate to choose a value of A equal to the sum of the direct and indirect annual costs estimated for the first year of the project. This assumption is in keeping with the overall accuracy of study estimates and allows for easier calculations.

Finally, notice diagram III. Here, the annual costs (A^1) are again equal, while the capital investment (P) is missing. Put simply, P has been incorporated into A^1, so that A^1 reflects not only the various annual costs but the investment as well. This was done by introducing another term, the *capital recovery factor* (CRF), defined as follows: "when multiplied by a present debt or investment, [the CRF] gives the uniform end-of-year payment necessary to repay the debt or investment in *n* years with interest rate *i*."[3] The product of the CRF and the investment (P) is the capital recovery cost (CRC):

$$CRC = CRF \times P \qquad (2.2)$$

where

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (2.3)$$

Therefore, A^1 is the sum of A and the CRC, or:

$$A^1 = A + CRF \times P \qquad (2.4)$$

In this context, *n* is the control system economic life, which, as stated above, typically varies from 10 to 20 years. The interest rate (*i*) used in this *Manual* is a pretax marginal rate of return on private investment of 7% (annual). This value, which could also be thought of as a "real private rate of return", is used in most of the OAQPS cost analyses and is in keeping with current OAQPS guidelines and the Office of Management and Budget recommendation for use in regulatory analyses.[4]

It may be helpful to illustrate the difference between *real* and *nominal* interest rates. The mathematical relationship between them is straight forward:[4]

$$(1+i_n) = (1+i)(1+r) \qquad (2.5)$$

where

i_n, i = the annual nominal and real interest rates, respectively

r = the annual inflation rate

Clearly, the real rate does not consider inflation and is in keeping with the expression of annual costs in constant (*i.e.*, real) dollars.

The above procedure using the pre-tax marginal (or real) rate of return on private investment is the appropriate method for assessing the costs from the perspective of the entity having to install the pollution control equipment. For example, costs developed with the above procedure can appropriately be used for answering questions concerning the market response to regulation like price increases, quantity adjustments, and reduced profitability.

In an idealized economy with perfectly competitive and complete markets, this private cost and the social cost would be equal. However, in a more realistic economy in which allocation of resources is distributed by taxes, credit restrictions, and other market imperfections, the cost to society is different than the private costs for capital expenditures. The costs to society are the relevant costs for use in answering questions about economic efficiency. For example, benefit cost analysis and cost-effectiveness analyses should focus on cost to society, not just the cost to the entity facing additional pollution control costs.

EPA has adopted a new approach, a two-stage approach, to discounting for social costs. This new approach begins with the same capital recovery costs (CRC) described above using the same 7% pre-tax marginal rate of return on private investment. The second step of the two-stage approach involves "discounting" both direct and indirect annual costs and CRC back to an initial date ("year 0") using a consumption rate of interest of 3%. (See Section 2.3.3 for an explanation of the discounting concept.) This results in a relatively higher cost of capital from society's perspective than from the perspective of the entity facing additional control cost. A detailed explanation of this procedure and when it should be employed is beyond the scope of this document. A fuller explanation is given in draft EPA guidelines [5]. However, it is mentioned here because the CRC and direct and indirect annual costs are inputs to the two-stage procedure and must be sufficiently itemized to allow use in the two-stage procedure.

2.3.3 Annualization and Discounting Methods

The above method of smoothing out the investment into equal end-of-year payments, is termed the *equivalent uniform annual cash flow* (EUAC) method.[3] In addition to its inherent simplicity, this method is very useful when comparing the costs of two or more alternative control systems (*i.e.*, those which are designed to control the same source to an equivalent degree). In fact, the EUAC's—or simply the total annual costs—of two competing systems may be compared *even if both the systems have different economic lives*, say 10 and 20 years. We recommend that the EUAC method be used for estimating control costs unless particular circumstances preclude its use.

Comparisons of systems with different economic lives cannot be made, however, using the other two annualization (*i.e.*, profitability analysis) methods—*present worth* (PW) and *internal rate of return* (IRR). The present worth (or discounted cash flow) method involves the discounting of all cash flows occurring after year 0 (*i.e.*, the system startup date) back to year 0. These cash flows are discounted by multiplying each by a discount factor, $\frac{1}{(1+i)^m}$, where *m* is the number of years from year 0 to the year in which the cash flow is incurred. The sum of these discounted cash flows is then added to the capital investment to yield the present worth of the project. The alternative having the highest present worth would be selected (in control system costing this is usually a negative number). But when comparing the present worths of alternative systems, the system lifetimes must be equal for the comparison to be valid.[3]

The third annualization method, internal rate of return (IRR), is similar to the present worth method, in that it involves the discounting of a series of unequal cash flows. However, where with the PW method the interest rate, *i*, is set beforehand, in the IRR method the interest rate is solved for (usually via trial-and-error) after arbitrarily setting the PW to zero. When comparing alternative systems, the one with the highest "IRR" (interest rate) is selected.[3] But here again, the alternative systems compared must have equal economic lives.

2.4 Estimating Procedure

The estimating procedure used in the *Manual* consists of five steps: (1) obtaining the *facility parameters* and *regulatory options* for a given facility; (2) roughing out the control system design; (3) sizing the control system components; (4) estimating the costs of these individual components; and (5) estimating the costs (capital and annual) of the entire system.

2.4.1 Facility Parameters and Regulatory Options

Obtaining the facility parameters and regulatory options involves not only assembling the parameters of the air pollution source (*i.e.*, the quantity, temperature, and composition of the emission stream(s)), but also compiling data for the facility's operation. (Table 2.1 lists examples of these.) Note that two kinds of facility parameters are identified—intensive and extensive. The former are simply those variables whose values are independent of quantity or dimensions—*i.e.*, the extent of the system. Conversely, extensive parameters encompass all size-dependent variables, such as the gas volumetric flow rate.

Like the facility parameters, the regulatory options are usually specified by others. These options are ways to achieve a predetermined emission limit. They range from no control to maximum control technically achievable. The option provided will depend, firstly, on whether the emission source is a stack (point source), a process leak (process fugitives source) or an unenclosed or partly enclosed area, such as a storage pile (area fugitives source). Stacks are normally controlled by "add-on" devices. As discussed above, this *Manual* will deal primarily with these add-on devices. (However, some of these devices can be used to control process fugitives in certain cases, such as a fabric filter used in conjunction with a building evacuation

system.) Add-ons are normally used to meet a specified emission level, although in the case of particulate emissions, they may also be required to meet an opacity level.

2.4.2 Control System Design

Step 2—roughing out the control system design—first involves deciding what kinds of systems will be priced (a decision that will depend on the pollutants to be controlled, exhaust gas stream conditions, and other factors), and what auxiliary equipment will be needed. When specifying the auxiliary equipment, several questions need to be answered:

- What type of hood (if any) will be needed to capture the emissions at the source?
- Will a fan be needed to convey the exhaust through the system?
- Is a cyclone or another pre-cleaner needed to condition the exhaust before it enters the control device?
- Will the captured pollutants be disposed of or recycled? How will this be done?
- Can the on-site utility capacity (*e.g.*, electricity) accommodate the added requirements of the control system?

The kinds of auxiliary equipment selected will depend on the answers to these and other site-specific questions. However, regardless of the source being controlled, each system will likely contain, along with the control device itself, the following auxiliaries:

- *Hood*, or other means for capturing the exhaust;

- *Ductwork*, to convey the exhaust from the source to, through, and from the control system;

- *Fan system* (fan, motor, starter, inlet/outlet dampers, etc.), to move the exhaust through the system;

- *Stack*, for dispersing the cleaned gas into the atmosphere.

2.4.3 Sizing the Control System

Once the system components have been selected, they must be sized. Sizing is probably the most critical step, because the assumptions made in this step will more heavily influence the capital investment than any other. Before discussing how to size equipment, we need to define the term.

parameter. (Table 2.2 lists examples of these parameters. For a full description of the ESP sizing procedure, see Chapter 6.)

Also listed in Table 2.2 are general parameters which must also be specified before the purchased cost of the system equipment can be estimated. Note that, unlike the control device parameters,

these may apply to any kind of control system. These parameters include materials of construction (which may range from carbon steel to various stainless steels to fiberglass-reinforced plastic), presence or absence of insulation, and the economic or useful life of the system. As indicated in Section 2.3.2, this last parameter is required for estimating the annual capital recovery costs. The lifetime not only varies according to the type of the control system, but with the severity of the environment in which it is installed. (Representative values for the system life and the other control device parameters will be presented in those chapters of the *Manual* covering them.)

Table 2.1: Facility Parameters and Regulatory Options

Facility Parameters

- Intensive

  - Facility status (new or existing, location)
  - Gas characteristics (temperature, pressure, moisture content)
  - Pollutant concentration(s) and/or particle size distribution

- Extensive

  - Facility capacity
  - Facility life
  - Exhaust gas flow rate
  - Pollutant emission rate(s)

Regulatory Options

- No control

- "Add-on" devices

  - Emission limits
  - Opacity limits

Table 2.2: Examples of Typical Control Device Parameters [6]

General

- Material of construction: carbon steel
- Insulated? Yes
- Economic life: 20 yr
- Redundancy[a]: none

Device-Specific

- Gas-to-cloth ratio ("critical parameter"): 3.0 to 1
- Pressure drop: 6.0 in w.c. (inches water column)
- Construction: standard (vs. custom)
- Duty: continuous (vs. intermittent)
- Filter type: shaker
- Bag material: polyester, 16-oz.

QUOTATION

(NOTE: Company name and address have been deleted.)

MAIL DROP # 12
U.S. EPA
RESEARCH TRIANGLE PARK
DURHAM, NC 27711

ATTN: MR. BILL VATAVUK

QUOTATION NO. 85523382
DATE 9-23-85
REFERENCE VERBAL - BUDGET

Thank you for your inquiry. We are pleased to submit our quotation as follows:

QUANTITY	DESCRIPTION	PRICE
1	ITEM #1 PREHEATER MODEL 191-19 SIZE #9 IMPERVITE SHELL & TUBE HEAT EXCHANGER WITH 55.8 SQ. FT. OF HEAT TRANSFER AREA AND CODE STAMPED	$ 7,147.00 EA.
1	ITEM #2 CONDENSER MODEL 191-19 SIZE #12 IMPERVITE SHELL & TUBE HEAT EXCHANGER WITH 74.5 SQ. FT. OF HEAT TRANSFER AREA AND CODE STAMPED	7,430.00 EA.
	APPROVAL DWG'S 2 - 3 WEEKS AFTER RECEIPT OF ORDER. THIS QUOTATION IS IN CONFIRMATION OF OUR PHONE CONVERSATION OF 9/18/85.	

ESTIMATED SHIPMENT 6 TO 8 WEEKS AFTER ☐ RECEIPT OF ORDER ☒ RECEIPT OF DRAWING APPROVAL

Prices are F.O.B. Net 30 Days.

Unless otherwise stated these prices are subject to acceptance within 30 days from date.

By

ANY PURCHASE ORDERS RESULTING FROM THIS QUOTATION WILL BE SUBJECT TO THE CONTRACT TERMS AND CONDITIONS PRINTED ON THE REVERSE SIDE OF THIS PAGE.

Figure 2.3: Typical Vendor Quotation

2.4.4 Estimating Total Capital Investment

2.4.4.1 General Considerations

The fourth step is estimating the *purchased equipment cost* of the control system equipment. These costs are available from this *Manual* for the most commonly used add-on control devices and auxiliary equipment. Each type of equipment is covered in a separate chapter. (See Table of Contents.)

Most of these costs, in turn, have been based on data obtained from control equipment vendors. There are scores of these firms, many of whom fabricate and erect a variety of control systems. [7] They have current price lists of their equipment, usually indexed by model designation. If the items for which costs are requested are fabricated, "off-the-shelf" equipment, then the vendor can provide a written quotation listing their costs, model designations, date of quotation, estimated shipment date, and other information. (See Figure 2.4 for a sample quotation.) Moreover, the quote is usually "F.O.B." (free-on-board) the vendor, meaning that no taxes, freight, or other charges are included. However, if the items are not off-the-shelf, they must be custom fabricated or, in the case of very large systems, constructed on-site. In such cases, the vendor can still give quotations—but will likely take much longer to do so and may even charge for this service, to recoup the labor and overhead expenses of his estimating department.

As discussed in Section 2.2 in this *Manual*, the total capital investment is factored from the purchased equipment cost, which in turn, is the sum of the base equipment cost (control device plus auxiliaries), freight, instrumentation, and sales tax. The values of these installation factors
depend on the type of the control system installed and are, therefore, listed in the individual *Manual* chapters dedicated to them.

The costs of freight, instrumentation, and sales tax are calculated differently from the direct and indirect installation costs. These items are factored also, but from the base equipment cost (F.O.B. the vendor(s)). But unlike the installation factors, these factors are essentially equal for all control systems. Values for these are as follows:

Cost	Range	Typical
Freight	0.01 - 0.10	0.05
Sales Tax	0 - 0.08	0.03
Instrumentation	0.05 - 0.30	0.10

The range in freight costs reflects the distance between the vendor and the site. The lower end is typical of major U.S. metropolitan areas, while the latter would reflect freight charges to remote locations such as Alaska and Hawaii.[6] The sales tax factors simply reflect the range of local and state tax rates currently in effect in the United States.[8]

The range of instrumentation factors is also quite large. For systems requiring only simple continuous or manual control, the lower factor would apply. However, if the control is intermittent and/or requires safety backup instrumentation, the higher end of the range would be applicable.[6] Finally, some "package" control systems (*e.g.*, incinerators covered in Chapter 3) have built-in controls, whose cost is included in the base equipment cost. In those cases, the instrumentation factor to use would, of course, be zero.

2.4.4.2 Retrofit Cost Considerations

The installation factors listed elsewhere in the *Manual* apply primarily to systems installed in new facilities. These factors must be adjusted whenever a control system is sized for, and installed in (*i.e.*, "retrofitted") an existing facility. However, because the size and number of auxiliaries are usually the same in a retrofit situation, the purchased equipment cost of the control system would probably not be different from the new plant purchased cost. An exception is the ductwork cost, for in many retrofit situations exceptionally long duct runs are required to tie the control system into the existing process.

Each retrofit installation is unique; therefore, no general factors can be developed.*
Nonetheless, some general information can be given concerning the kinds of system modifications one might expect in a retrofit:

1. *Auxiliaries*. Again, the most important component to consider is the ductwork cost. In addition, to requiring very long duct runs, some retrofits require extra tees, elbows, dampers, and other fittings.

---

* Retrofit factors for *specific* applications (coal-fired boiler controls) have been developed. See references [9] and [10].

2. *Handling and Erection.* Because of a "tight fit," special care may need to be taken when unloading, transporting, and placing the equipment. This cost could increase significantly if special means (*e.g.*, helicopters) are needed to get the equipment on roofs or to other inaccessible places.

3. *Piping, Insulation, and Painting.* Like ductwork, large amounts of piping may be needed to tie in the control device to sources of process and cooling water, steam, etc. Of course, the more piping and ductwork required, the more insulation and painting will be needed.

4. *Site Preparation.* Unlike the other categories, this cost may actually decrease, for most of this work would have been done when the original facility was built.

5. *Off-Site Facilities*. Conceivably, retrofit costs for this category could be the largest. For example, if the control system requires large amounts of electricity (*e.g.*, a venturi scrubber), the source's power plant may not be able to service it. In such cases, the source would have to purchase the additional power from a public utility, expand its power plant, or build another one. In any case, the cost of electricity supplied to that control system would likely be higher than if the system were installed in a new source where adequate provision for its electrical needs would have been made.

6. *Engineering*. Designing a control system to fit into an existing plant normally requires extra engineering, especially when the system is exceptionally large, heavy, or utility-consumptive. For the same reasons, extra supervision may be needed when the installation work is being done.

7. *Lost Production.* This cost is incurred whenever a retrofit control system cannot be tied into the process during normally scheduled maintenance periods. Then, part or all of the process may have to be temporarily shut down. The net revenue (*i.e.*, gross revenue minus the *direct* costs of generating it) lost during this shutdown period is a bonafide retrofit expense.

8. *Contingency.* Due to the uncertain nature of many retrofit estimates, the contingency (*i.e.*, uncertainty) factor in the estimate should be increased. From the above points, it is apparent that some or most of these installation costs would increase in a retrofit situation.However,there may be other cases where the retrofitted installation cost would be less than the cost of installing the system in a new plant. This could occur when one control device, say an ESP, is being replaced by a more efficient unit—a baghouse, for example. The ductwork, stack, and other auxiliaries for the ESP might be adequate for the new system, as perhaps would be the support facilities (power plant, etc.).

2.4.5 Estimating Annual Costs

Determining the total annual cost is the last step in the estimating procedure. As mentioned in Section 2.2 the TAC is comprised of three components—direct and indirect annual costs and recovery credits. Unlike the installation costs, which are factored from the purchased equipment cost, annual cost items are usually computed from known data on the system size and operating mode, as well as from the facility and control device parameters.

Following is a more detailed discussion of the items comprising the total annual cost. (Values/factors for these costs are also given in the chapters for the individual devices.)

2.4.5.1 Raw Materials

Raw materials are generally not required with control systems. Exceptions would be chemicals used in gas absorbers or venturi scrubbers as absorbents or to neutralize acidic exhaust gases (*e.g.*, hydrochloric acid). Chemicals may also be required to treat wastewater discharged by scrubbers or absorbers before releasing it to surface waters. But, these costs are only considered when a wastewater treatment system is exclusively dedicated to the control system. In most cases, a pro-rata waste treatment charge is applied. (See also discussion below on Waste Treatment and Disposal.)

Quantities of chemicals required are calculated via material balances, with an extra 10 to 20% added for miscellaneous losses. Costs for chemicals are available from the *Chemical Marketing Reporter* and similar publications.

2.4.5.2 Operating Labor

The amount of labor required for a system depends on its size, complexity, level of automation, and operating mode (*i.e.*, batch or continuous). The labor is usually figured on an hours-per-shift basis. As a rule, though, data showing explicit correlations between the labor requirement and capacity are hard to obtain. One correlation found in the literature is logarithmic:[11]

$$\frac{L_2}{L_1} = \left(\frac{V_2}{V_1}\right)^y \tag{2.6}$$

where

L_1, L_2 = labor requirements for systems 1 and 2
V_1, V_2 = capacities of systems 1 and 2 (as measured by the gas flow rate, for instance)

y = 0.2 to 0.25 (typically)

The exponent in Equation 2.6 can vary considerably, however. Conversely, in many cases, the amount of operator labor required for a system will be approximately the same regardless of its size.

A certain amount must be added to operating labor to cover supervisory requirements. Fifteen per cent of the operating labor requirement is representative.[12]

To obtain the annual labor cost, multiply the operating and supervisory labor requirements(labor-hr/operating-hr) by the respective wage rates (in $/labor-hr) and the system operating factor (number of hours per year the system is in operation). The wage rates also vary widely, depending upon the source category, geographical location, etc. These data are tabulated and periodically updated by the U.S. Department of Labor, Bureau of Labor Statistics, in its *Monthly Labor Review* and in other publications. Finally, note that these are base labor rates, which do *not* include payroll and plant overhead. (See Overhead discussion below.)

2.4.5.3 Maintenance

Maintenance labor is calculated in the same way as operating labor and is influenced by the same variables. The maintenance labor rate, however, is normally higher than the operating labor rate, mainly because more skilled personnel are required. A 10% wage rate premium is typical.[12]

Further, there are expenses for maintenance materials—oil, other lubricants, duct tape, etc., and a host of small tools. Costs for these items can be figured individually, but since they are normally so small, they are usually factored from the maintenance labor. Reference [11] suggests a factor of 100% of the maintenance labor to cover the maintenance materials cost.

2.4.5.4 Utilities

This cost category covers many different items, ranging from electricity to compressed air. Of these, only electricity is common to all control devices, where fuel oil and natural gas are generally used only by incinerators; water and water treatment, by venturi scrubbers, quenchers, and spray chambers; steam, by carbon adsorbers; and compressed air, by pulse-jet fabric filters.

Techniques and factors for estimating utility costs for specific devices are presented in their respective sections. However, because nearly every system requires a fan to convey the exhaust gases to and through it, a general expression for computing the fan electricity cost (C_e) is given here:[6]

$$C_e = \frac{0.746\ Q\ \Delta P\ s\theta\ p_e}{6356\eta} \tag{2.7}$$

where

Q	=	gas flow rate (*actual* ft^3 /min)
ΔP	=	pressure drop through system (inches of water, column) (Values for ΔP are given in the chapters covering the equipment items.)
s	=	specific gravity of gas relative to air (1.000, for all practical purposes)
θ	=	operating factor (hr/yr)
η	=	combined fan and motor efficiency (usually 0.60 to 0.70)
p_e	=	electricity cost ($/kwhr)

A similar expression can be developed for calculating pump motor electricity requirements.

2.4.5.5 Waste Treatment and Disposal

Though often overlooked, there can be a significant cost associated with treating and/or disposing of waste material captured by a control system that neither can be sold nor recycled to the process.

Liquid waste streams, such as the effluent from a gas absorber, are usually processed before being released to surface waters. The type and extent of this processing will, of course, depend on the characteristics of the effluent. For example, the waste can first be sent to one (or more) clarifiers, for coagulation and removal of suspended solids. The precipitate from the clarifier is then conveyed to a rotary filter, where most of the liquid is removed. The resulting filter cake is then disposed of, via landfilling, for example.

The annual cost of this treatment can be relatively high—$1.00 to $2.00/thousand gallons treated or more.[13] The (non-hazardous) solid waste disposal costs (via landfilling, for example) typically would add another $20 to $30/ton disposed of.[14] This, however, would *not* include transportation to the disposal site. Disposal of hazardous waste (which may *not* be landfilled) can be much more costly—$200 to $300/ton or more. More information on these technologies and their costs is found in References [13] and [14].

2.4.5.6 Replacement Parts

This cost is computed separately from maintenance, because it is a large expenditure, incurred one or more times during the useful life of a control system. This category includes such items as carbon (for carbon absorbers), bags (for fabric filters) and catalyst (for catalytic incinerators), along with the labor for their installation.

The annual cost of the replacement materials is a function of the initial parts cost, the parts replacement labor cost, the life of the parts, and the interest rate, as follows:

$$CRC_p = (C_p + C_{pl})\ CRF_p \tag{2.8}$$

where

CRC_p	=	capital recovery cost of replacement parts ($/yr)
C_p	=	initial cost of replacement parts, *including* sales taxes and freight ($)
C_{pl}	=	cost of parts-replacement labor ($)
CRF_p	=	capital recovery factor for replacement parts (defined in Section 2.3).

In the *Manual* methodology, replacement parts are treated the same as any other investment, in that they are also considered an expenditure that must be amortized over a certain period. Also, the useful life of the parts (typically 2 to 5 years) is generally less than the useful life of the rest of the control system.

Replacement-part labor will vary, depending upon the amount of the material, its workability, accessibility of the control device, and other factors.

2.4.5.7 Overhead

This cost is easy to calculate, but often difficult to comprehend. Much of the confusion surrounding overhead is due to the many different ways it is computed and to the several costs it includes, some of which may appear to be duplicative.

There are, generally, two categories of overhead, *payroll* and *plant*. Payroll overhead includes expenses directly associated with operating, supervisory, and maintenance labor, such as: workmen's compensation, Social Security and pension fund contributions, vacations, group insurance, and other fringe benefits. Some of these are fixed costs (*i.e.*, they must be paid regardless of how many hours per year an employee works). Payroll overhead is traditionally computed as a percentage of the total annual labor cost (operating, supervisory, and maintenance).

Conversely, plant (or "factory") overhead accounts for expenses not necessarily tied to the operation and maintenance of the control system, including: plant protection, control laboratories, employee amenities, plant lighting, parking areas, and landscaping. Some estimators compute plant overhead by taking a percentage of all labor plus maintenance materials [11], while others factor it from the total labor costs alone.[2]

For study estimates, it is sufficiently accurate to combine payroll and plant overhead into a single indirect cost. This is done in this *Manual*. Also, overhead is factored from the sum of all labor (operating, supervisory, and maintenance) plus maintenance materials, the approach recommended in reference [11]. The factors recommended therein range from 50 to 70% [11] An average value of 60% is used in this *Manual*.

2.4.5.8 Property Taxes, Insurance, and Administrative Charges

These three indirect operating costs are factored from the system total capital investment, and typically comprise 1, 1, and 2% of it, respectively. Property taxes and insurance are self-explanatory. Administrative charges covers sales, research and development, accounting, and other home office expenses. (It should not be confused with plant overhead, however.) For simplicity, the three items are usually combined into a single, 4% factor. This value, incidentally, is standard in all OAQPS cost analyses.

2.4.5.9 Capital Recovery

As discussed in Section 2.3, the annualization method used in the *Manual* is the equivalent uniform annualized cost method. Recall that the cornerstone of this method is the capital recovery factor which, when multiplied by the total capital investment, yields the capital recovery cost. (See Equation 2.2.)

However, whenever there are parts in the control system that must be replaced before the end of its useful life, Equation 2.2 must be adjusted, to avoid double-counting.

That is:

$$CRC_s = CRF_s\,[TCI - (C_p + C_{pl})] \tag{2.9}$$

where

CRC_s = capital recovery cost for control system ($/yr)
TCI = total capital investment for entire system ($)
CRF_s = capital recovery factor for control system.

The term ($C_p + C_{pl}$) accounts for the cost of those parts (including sales taxes and freight) that would be replaced during the useful life of the control system and the labor for replacing them. Clearly, CRF_s and CRF_p will not be equal unless the control system and replacement part lives are equal.

References

[1] Perry, Robert H., and Chilton, Cecil H., *Perry's Chemical Engineers' Handbook* (Fifth Edition), McGraw-Hill, New York, 1973, pp. 25-12 to 25-16.

[2] Humphries, K. K. and Katell, S., *Basic Cost Engineering*, Marcel Dekker, New York, 1981, pp. 17-33.

[3] Grant, E.L., Ireson, W.G., and Leavenworth, R.S., *Principles of Engineering Economy*, Sixth Edition, John Wiley & Sons, New York, 1976.

[4] CEIS (OAQPS) Cost Guidance Memo #2: "Implementing OMB Circular A-94: *Guidelines and Discount Rates for Benefit Cost Analysis of Federal Programs*," March 18, 1993.

[5] Scheraga, Joel D., Draft of "Supplemental Guidelines on Discounting in the Preparation of Regulatory Impact Analyses", Office of Policy, Planning and Evaluation, U.S. EPA, March 31, 1989.

[6] Vatavuk, W.M. and Neveril, R.B., "Estimating Costs of Air-Pollution Control Systems—Part I: Parameters for Sizing Systems," *Chemical Engineering*, October 6, 1980, pp. 165-168.

[7] *Pollution Equipment News 1996 Buyer's Guide*, Rimbach Publishing, Pittsburgh, 1996.

[8] Internal Revenue Service, Form 1040, 1985.

[9] Shattuck, D.M., et al., *Retrofit FGD Cost-Estimating Guidelines*. Electric Power Research Institute, Palo Alto, CA (CS-3696, Research Project 1610-1), October 1984.

[10] Kaplan, N., et al., "Retrofit Costs of SO_2 and NO_x Control at 200 U.S. Coal-Fired Power Plants," Pittsburgh Coal Conference, 1990.

[11] Peters, M.S. and Timmerhaus, K.D., *Plant Design and Economics for Chemical Engineers* (Third Edition), McGraw-Hill, New York, 1980.

[12] Vatavuk, W.M. and Neveril, R.B., "Estimating Costs of Air Pollution Control Systems—Part II: Factors for Estimating Capital and Operating Costs," *Chemical Engineering*, November 3, 1980, pp. 157-162.

[13] Vatavuk, W.M. and Neveril, R.B., "Estimating Costs of Air-Pollution Control Systems—Part XVII: Particle Emissions Control," *Chemical Engineering*, April 2, 1984, pp. 97-99.

[14] The RCRA *Risk-Cost Analysis Model*, U.S. Environmental Protection Agency, Office of Solid Waste, January 13, 1984.